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Investigation on Properties of ECC Incorporating Crumb Rubber of Different Sizes

Zhigang Zhang¹, Hui Ma¹ and Shunzhi Qian²*

Received 1 August 2014, accepted 5 May 2015 doi:10.3151/jact.13.241

Abstract

In the past decades, incorporating crumb rubber into concrete has attracted attention in the field of building materials due to the properties improvement it brought. In this study, crumb rubber of two particle sizes (40CR and 80CR, which have a sieve size of 400 μm and 220 μm, respectively) is incorporated into engineering cementitious composite (ECC) material to replace silica sand. Furthermore, three different replacement percentages (0, 15%, 25% by volume) for each crumb rubber size are conducted in this study. The influence of crumb rubber on the ECC is revealed via density, compressive strength, flexural performance, drying shrinkage, restrained shrinkage and environment footprint. The experimental results show that the incorporation of crumb rubber into ECC increases bending deformation capacity, decrease density and compressive strength. While the free drying shrinkage of ECC increases with the addition of crumb rubber, lesser crack number, crack width and cracking tendency were found in the restrained ring test when compared to ECC without crumb rubber. In terms of crumb rubber size, ECC with smaller crumb rubber appear to have lower density and higher bending defamation capacity and shrinkage than those with larger crumb rubber. In addition, incorporating crumb rubber into ECC reduces CO₂ emission, thus improve the greenness of ECC to a certain degree.

1. Introduction

With the development of the rubber and automobile industries, the growing amount of waste rubber, rubber products and angle scrap produced from scrap tires has raised ever-increasing environmental concern. Meanwhile, the disposal of waste tire rubber has been a very thorny problem to governments in the world. Generally, the cheapest and easiest way to dispose the used tires is by burning them. However, the pollution caused by enormous amount of smoke during burning makes this method so unacceptable that it is prohibited by law in many countries (Siddique and Naik 2004; Sukontasukkul and Chaikaew 2006). Besides that, the discarded tires are also disposed by burying with other industrial waste in landfills or stockpiling in huge dumps. However, the stockpiles not only hazard environment potentially but also provide breeding grounds for rats, mice, vermin and mosquitoes (Naik and Singh 1991; Singh 1993). Furthermore, landfills has become increasingly unaccepted due to limited availability of sites for waste disposal, and some countries such as France has issued new law to forbid any new landfill. Huge volume of accumulated used tires has been the main waste management problem. Therefore, recycling and utilization of the waste tires seems to be necessary.

In the past two decades, significant research work has been carried out to incorporate rubber powder produced by grinding used tires into cement-based materials like concrete (Topcu 1995; Garrick 2005; Sukontasukkul and Chaikaew 2006; Hernández-Olivares et al. 2007; Khatib and Bayomy 1999; Donaldson 2010). After the addition of tire rubber powder, the overall research results indicated a remarkable reduction in strength and stiffness properties of the concrete. Despite the significant decrease in the strength properties, the composites still satisfy the basic requirements of construction materials (Ho et al. 2008). Furthermore, the addition of crumb rubber can also decrease density of concrete while increase drying shrinkage (Sukontasukkul and Tiamlom 2012; Ho et al. 2012). Nevertheless, the cracking resistance was improved due to the enhanced strain capacity (Huang et al. 2013). In addition, replacement of natural aggregate with rubber particles provided significant increase in toughness and ductility as well as better damping capacity of the concretes (Nehdi and Khan 2001; Hernandez-Olivarez et al. 2002; Gesog and Guneyisi 2007; Reda Taha et al. 2008). Considering the above benefits waste rubber powder brought into concrete, it is worthwhile to conduct some research on the influence of crumb rubber on the properties of engineered cementitious composite (ECC).

ECC is a kind of high-performance fiber-reinforced cementitious composites (HPF RCC) with a unique property of high ductility with medium fiber content, which was designed based on micromechanics theory by Victor Li at 1990s (Li 1993). Tensile strain capacity of ECC materials ranges from 3 to 5%, which have been demonstrated using polyethylene fibers and polyvinyl alcohol (PVA) fibers with fiber volume percentage less

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than 2% (Li 1998; 2002). Unlike the continuous widening of one localized crack in normal concrete, multiple tiny cracks (typically below 100 μm) developed sequentially in ECC before final fracture which contributes its large strain capacity. With such tiny cracks in ECC, the water permeability coefficient and chloride diffusion property were found to be nearly the same as that of sound concrete (Sahmaran et al. 2007; Lepech and Li 2009). From this perspective, the cracks formation (which is inevitable to concrete materials) in ECC is expected to have little impact on transport properties and durability. The associated high fracture toughness, high ductility and tight crack width control capacity make ECCs an ideal material to improve durability of the civil infrastructures, thus prolong its service life.

Although the utilization of waste rubber in concrete has attracted attentions in the field of building materials in the past decades, the research on ECC incorporating crumb rubber is very limited. One most relevant paper was published by Huang et al. recently (2013). They carried out some investigations based on recycled tire rubber, in their study; they found that the addition of crumb rubber can increase ECC’s tensile strain capacity and enhanced its cracking resistance. Nevertheless, they did not investigate the effect of crumb rubber size on ECC’s properties, flexural properties, as well as restrained shrinkage and impact on environment.

ECC with crumb rubber replacement of silica sand (three replacement percentages are referred for both crumb rubber size in this study) is proposed. This paper focuses on the density, flexural performance, compressive strength, drying shrinkage and restrained shrinkage of ECC with the incorporation of crumb rubber. Finally, the environment footprint is also given. In the following sections, the experimental program is introduced firstly. The experimental program is useful in understanding the process of experiment. Then the experiment results and discussion are reported.

### Table 1 Properties of PVA fibers.

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Diameter (μm)</th>
<th>Length (mm)</th>
<th>Tensile strength (MPa)</th>
<th>Modulus (GPa)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kuraray PVA fiber</td>
<td>39</td>
<td>8</td>
<td>1600</td>
<td>42</td>
<td>1.3</td>
</tr>
<tr>
<td>Chinese PVA fiber</td>
<td>30</td>
<td>12</td>
<td>1200</td>
<td>22</td>
<td>1.3</td>
</tr>
</tbody>
</table>

#### 2. Experimental programs

### 2.1 Materials and mix proportions

In this paper, ingredients include ordinary Portland cement, fly ash (FA), silica sand, crumb rubber, water, Kuraray polyvinyl alcohol (PVA) fiber and polycarboxylate-based high water reducer (HRWR) were used in the production of ECC mixtures. The geometrical and mechanical properties of PVA fibers are described in Table 1. The parameters of Chinese PVA fiber listed in Table 1 will be used to discuss the influence of crumb rubber on interface parameters in section 3.3. The look of crumb rubber particle is shown in Fig. 1. Figure 2 presents the grade curves of silica sand and crumb rubber, which shows that the particle size distribution of 80CR is very close to that of silica sand. The density of two kinds of crumb rubber and silica sand is 1.19 g/cm³ for 80CR, 1.27 g/cm³ for 40CR and 2.60 g/cm³, respectively.

To investigate the influence of incorporation of crumb rubber on the performance of ECC material, five ECC mixtures with the same water-binder ratio of 0.25 and the same fly ash-cement ratio of 2.2 were adopted in this study. The mix proportion of all mixtures is listed in Table 2. The 80CR is used in M2 and M3, while 40CR is used in M4 and M5. The variable parameter in ECC mixture is the crumb rubber replacement ratio (15%, 25% by volume of silica sand). The standard mixture without crumb rubber is also studied as the control mixture.

Five ECC mixtures were all used for four-point bending test, compressive strength and free drying shrinkage. All ECC mixtures were mixed in the standard mixing process. All solid ingredients including cement, fly ash, silica sand, and crumb rubber were mixed dry for 3 minutes before adding water. Water and HRWR were then added into the dry mixture for another 3 minutes. Then PVA fiber were slowly added into the mortar and mixed for 5 minutes until fibers were dispersed well. The

![Fig. 1 The look of Crumb rubber particles.](image)

![Fig. 2 Grade curve of crumb rubber and silica sand.](image)
2.2 Specimens preparation and testing

For each mixture, three specimens were prepared for compressive test and bending test. The dimensions of compressive and bending specimen were 70.7×70.7×70.7 mm and 400×70×16 mm, respectively. The compressive strength and bending properties were obtained by taking average the results of three specimens.

Four-point bending test was used to evaluate the bending deformation capacity of ECC. The test was conducted under quasi-static loading condition with deformation control of 0.0125 mm/s. The full span length was 300 mm with middle span of 100mm. During the test, the loading stress and loading point displacement were recorded by computerized data recording system. The load-displacement behavior, first cracking strength, flexural strength and toughness index can be obtained from this test. The crack width and the crack number were measured after unloading using portable microscope with minimum scale of 10 μm. For each mixture, the average crack width is obtained from the crack number of 30-50 for each specimen.

To study the variation of matrix fracture toughness after incorporating crumb rubber, the fracture toughness of M1, M2, and M3’s matrix was measured with samples’ dimension of 304.8×38.1×76.2 mm, according to ASTM E399 using a three-point bending test setup (2013). The full span length of bottom support for the beam was 254 mm and the notch depth (at the longitudinal center of the beam) to beam height ratio was 0.4. During the test, the fracture load was recorded and the matrix fracture toughness was calculated using the recording data, in accordance with ASTM E399.

To investigate free drying shrinkage of ECCs, three specimens were prepared for each mixture with dimensions of 285×25×25 mm in accordance with ASTM C1581/C1587 (2009). A 75 mm thick layer of ECC mixture was casted around a rigid steel ring with a height of 150 mm and inner-outers diameters of 330 mm and 405 mm, respectively. After casting, the top surface of fresh ECC was sealed by silica rubber immediately. The ring specimens were cured in the mold for 24 h before removing the outer ring mold, and then exposed in air at temperature of 23±3 °C and relative humidity of 20±3%. To track the development of restrained shrinkage, two strain gages were attached at the mid-height of inner surface of the steel ring which restrains the shrinkage of ECC specimens. A uniform radial pressure will be exerted on the steel ring due to the shrinkage of ECC, which in turn induces tensile hoop stresses and subsequent cracking on the ECC mortar specimens. For data recording convenience, the strain gages were connected to a data acquisition system in a one fourth-bridge configuration which acquires strain data at 30 min intervals. The steel ring strain measurements were taken immediately after casting and ended after 28 days curing. Then, the crack width and crack length were measured using portable microscope and millimeter with accuracy of 10 μm and 1 mm, respectively.

3. Results and discussions

3.1 Density of ECCs

Results on density are given in Table 3. The density of ECC is found to decrease with the increasing percentage of crumb rubber incorporation. Two possible reasons may explain that. Firstly, the specific gravity of crumb rubber is low (about 45% of the silica sand). Secondly, air bubbles may be trapped at the crumb rubber surfaces during mixing process due to nature non-polar property of rubber, consequently, increases the air content (Khatib and Bayomy 1999). The trapped air bubble at crumb rubber surface submerged in water observed using opti-

Table 2 Mixture proportion of ECC mixture (g/L).

<table>
<thead>
<tr>
<th>Crumb rubber</th>
<th>Mix ID</th>
<th>Cement</th>
<th>Fly ash</th>
<th>Sand</th>
<th>Crumb rubber</th>
<th>Water</th>
<th>HRWR</th>
<th>PVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>395</td>
<td>868</td>
<td>459</td>
<td>0</td>
<td>312</td>
<td>6</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>395</td>
<td>868</td>
<td>390</td>
<td>31</td>
<td>312</td>
<td>6</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>M3</td>
<td>395</td>
<td>868</td>
<td>344</td>
<td>51</td>
<td>312</td>
<td>6</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>M4</td>
<td>395</td>
<td>868</td>
<td>390</td>
<td>33</td>
<td>312</td>
<td>6</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>M5</td>
<td>395</td>
<td>868</td>
<td>344</td>
<td>55</td>
<td>312</td>
<td>6</td>
<td>26</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Density of ECC (kg/m³).

<table>
<thead>
<tr>
<th>Crumb rubber size</th>
<th>Mix ID</th>
<th>Sand replacement (% Vol.) by Crumb rubber</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0</td>
<td></td>
<td>1830</td>
</tr>
<tr>
<td>80CR</td>
<td>15</td>
<td></td>
<td>1660</td>
</tr>
<tr>
<td>80CR</td>
<td>25</td>
<td></td>
<td>1600</td>
</tr>
<tr>
<td>40CR</td>
<td>15</td>
<td></td>
<td>1710</td>
</tr>
<tr>
<td>40CR</td>
<td>25</td>
<td></td>
<td>1640</td>
</tr>
</tbody>
</table>
3.2 Compressive strength

The material compressive strength for different mixtures can be found in Fig. 4. As listed in Fig. 4, after incorporation of crumb rubber, compressive strength of ECC mixtures decreases about 35% compared with control mixture M1. Nevertheless, there is no clear difference of compressive strength between crumb rubber ECC specimens with different replacement ratios and crumb rubber sizes. The loss of compressive strength of ECC can be attributed to the increment of porosity caused by the addition of crumb rubber (Bignozzi and Sandrolini 2006; Topcu and Bilir 2009), as well as the unavoidable space generated due to the separation of crumb rubber from hydration products under compression, as shown in Fig. 5.

3.3 Flexural performance of ECCs

Three specimens were tested for each mixture to reveal the effect of crumb rubber on flexural behavior. As shown in Fig. 6, all ECC specimens exhibit very large deflection capacity under the four-point bending test. The representative flexural stress-load point deflection curves for all mixtures are presented in Fig. 7. As shown in the flexural stress–deflection curves, the end point of the linear stage is defined as the first flexural cracking strength, while the maximum flexural stress and corresponding deflection with it are defined as the flexural...
strength and flexural deflection capacity, respectively.

Figure 8 presents the influence of crumb rubber incorporated into ECC on the deflection capacity, first flexural cracking and flexural strength of ECC mixtures at 60 days. The deflection capacity of ECC increases with the amount of crumb rubber. The average deflection of all ECC mixtures changes from 12.6 mm to 31.3 mm. The deflection of ECC incorporating crumb rubber is 1.4–2.5 times that of control mixture. The effect of crumb rubber on deflection capacity is more pronounced when smaller sized crumb rubber is used. At the same replacement percentage, ECC mixed with crumb rubber No. 80 (80CR) exhibits larger deflection capacity than the one mixed with crumb rubber No. 40 (40CR). Flexural deflection capacity of ECC material, which can reflect its ductility (Qian 2007), strongly depends on crumb rubber replacement level (as shown in Fig. 7 and Fig. 8).

The increase of ductility with the addition of crumb rubber can be explained from the micro-mechanics design theory of ECC materials. To enable more saturated micro-cracking and robust ductility of ECC, a sufficient margin between crack tip toughness \( J_{\text{tip}} \) (proportional to \( K_m^2 \)) and complementary energy \( J_b' \) (calculated from fiber bridging stress versus crack opening \( \sigma-\delta \) curve) is needed, and more details can be found in references (Marshall and Cox 1988, Li and Leung 1992). A larger strain-hardening index SHI (\( J_b'/J_{\text{tip}} \)) indicates a better chance for saturated multiple cracking.

In the three-point bending test determining the matrix’s toughness, the load versus displacement relationship of the notched beam specimen is shown in Fig. 9. It is found that the load increase linearly with the displacement, therefore the maximum load is adopted to be the fracture force to calculate matrix’s fracture toughness \( K_m \), in accordance with ASTM E399 (2013). As shown in Fig. 9 and Table 4, the fracture force decreases with the addition of crumb rubber, indicating diminishing matrix’s fracture toughness \( K_m \). As a result, the matrix’s crack tip toughness \( J_{\text{tip}} = K_m^2/E_m \) reduces from 17.7 to 9.2 J/m\(^2\), whereby the elastic modulus \( E_m \) is referenced from Zhang et al. (2015).

Recently co-author Hui Ma investigated the influence of crumb rubber on the interface properties between Chinese PVA fiber and matrix by conducting single fiber pull-out test which has not been published. The detailed experiment set-up preparation can be found in the reference (Redon et al 2001). The chemical bonding \( (G_d) \), frictional bond \( (\tau_0) \) and slip-hardening coefficient \( (\beta) \) was obtained from Hui Ma’s test. The Chinese PVA

**Table 4 Multiple micro-cracking parameters of ECCs.**

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Fracture force (N)</th>
<th>( K_m ) (MPa√m)</th>
<th>( E_m ) (GPa)</th>
<th>( G_d ) (J/m(^2))</th>
<th>( \tau_0 ) (MPa)</th>
<th>( \beta )</th>
<th>( f )</th>
<th>( f' )</th>
<th>( J_{\text{tip}} ) (J/m(^2))</th>
<th>( J_b' ) (J/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1-control</td>
<td>980</td>
<td>0.58</td>
<td>19</td>
<td>2.18</td>
<td>1.27</td>
<td>0</td>
<td>0.2</td>
<td>0.33</td>
<td>17.7</td>
<td>23.7</td>
</tr>
<tr>
<td>M2-80CR(15%)</td>
<td>733</td>
<td>0.43</td>
<td>14</td>
<td>1.86</td>
<td>1.36</td>
<td>0</td>
<td>0.2</td>
<td>0.33</td>
<td>13.2</td>
<td>27.1</td>
</tr>
<tr>
<td>M3-80CR(25%)</td>
<td>606</td>
<td>0.36</td>
<td>14</td>
<td>1.51</td>
<td>0.91</td>
<td>0</td>
<td>0.2</td>
<td>0.33</td>
<td>9.2</td>
<td>27.8</td>
</tr>
</tbody>
</table>
fiber’s parameters and micromechanical parameters used to calculate \( J_b \) are summarized in Table 1 and Table 4, respectively (Courtesy of Mr. Hui Ma). The values of snubbing coefficient \((f)\) and in-situ fiber strength reduction factor \((f_s)\) shown in Table 4 were adopted from Wang’s PhD dissertation and Kanda’s previous work, respectively (Kanda and Li 1998; Wang 2005). As shown in Table 4, both \( G_d \) and \( \tau_p \) show decreasing trend with the addition of crumb rubber. The value of \( \beta \) equals to 0, which seems to suggest that no slip-hardening occurred during the Chinese PVA fiber’s pull-out process from the particular matrix. This might change for our case as Kuraray fibers were adopted in our study; nevertheless it is adopted for estimation as this is the closest results we can find. A fiber bridging mathematical models based on two-way fiber pull-out consideration developed by Yang et al. (2008) was used to calculate the value of \( J_b \). After calculation based on the above micromechanical parameters, the complementary energy \( J_g \) has a slight growth as the crumb rubber content in ECC increase. Combining effect of decreasing \( J_g \), and increasing \( J_b \) with the addition crumb rubber results in enhanced strain-hardening index \( SHI (=J_b/J_g) \), which is favourable for saturated multiple cracking behavior and ductility.

As shown in Fig. 8, the first flexural cracking strength of ECC mixtures decreases with the addition of crumb rubber contributed by the decrease of matrix’s fracture toughness making it easier to crack. For example, compared with M1, first flexural cracking strength of M2, M3 decreases 16% and 21%, respectively. In addition to first flexural cracking strength, the flexural strength of ECC mixtures incorporating crumb rubber also shows a downward trend, which indicates a decrease in fiber bridging capacity by incorporating crumb rubber (Li 2012). This may be attributed that large amount of crumb rubber leads to reduced contact area between fibers and matrix which is very similar to the phenomenon observed in latex-modified ECC (Chen et al 2014), thus lowering the fiber/matrix interfacial bond.

Table 5 lists the load-deflection response of ECCs, as list, first flexural cracking energy and fracture energy are evaluated by integrating areas under load-deflection curve of ECC corresponding to first flexural cracking and flexural strength. Toughness index is defined as the ratio of fracture energy to first flexural cracking energy, which indicates the normalized plastic energy dissipation capacity. As listed in Table 5, incorporating crumb rubber can increase the toughness index. For ECC with incorporating crumb rubber of 80CR, compared with M1, the toughness index increase 8% and 72%. For ECC with incorporating crumb rubber of 40CR, it increases 5% and 25%. The results show that incorporating finer crumb rubber can effectively improve ECC’s energy dissipation capacity more.

Figure 10 shows the crack pattern of ECCs under bending test. As observed from Fig. 10 that incorporating crumb rubber into ECC decrease crack width while increase crack number, denoting the replacement of silica sand with crumb rubber can help strain-hardening behavior of ECC. The crack width of concrete has a significant impact on its transport properties, thus influence its service life. The reduction in crack width is beneficial to its durability (Gerard et al 1997; Hearn N 1999; Lawler et al 2002). In addition to the above results, the crack width of ECC specimen incorporated with 80CR crumb rubber is tighter with more cracks, compared to ECC with 40CR crumb rubber. It shows the positive effect of incorporating 80CR crumb rubber on cracking behavior is more pronounced.

3.4 Drying shrinkage of ECC with crumb rubber

The results of drying shrinkage test of ECC mixtures up to 90 days are shown in Fig. 11. Each data point represents an average measurement of three specimens. As displayed in Fig. 11 drying shrinkage of ECCs is much higher than that of normal concrete, which is attributed to the absence of coarse aggregate in ECC matrix. For all ECC specimens, drying shrinkage achieve a steady stage after 21 days. As illustrated in Fig. 12, maximum drying shrinkage of all specimens ranges from \( 1050 \times 10^{-6} \) to \( 1660 \times 10^{-6} \) at the age of 90 days. Meanwhile, ECCs incorporated with crumb rubber exhibit higher drying shrinkage than that of control mixture at all test age. A plausible explanation for this increase is that the modulus of rubber is much lower and much more flexible than silica sand, thus reducing the internal restraint to shrinkage.

In addition, in term of crumb rubber content, drying shrinkage of ECC increases as percentage of crumb rubber
rubber replacement increase. In term of rubber size, drying shrinkage of ECC for the 80CR (smaller size) is larger than that of 40CR case under the same crumb rubber content.

In previous study, considering a 2-D slab under restraint at its ends, Li and Henrik defined a restrained shrinkage cracking potential parameter $P$ as stated in equation (1) (2004).

$$P = \varepsilon_{sh} - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp})$$

Where $\varepsilon_{sh}$ is the free shrinkage strain of material, $\varepsilon_e$ is its elastic tensile strain capacity, $\varepsilon_i$ is its inelastic tensile strain capacity, and $\varepsilon_{cp}$ is its tensile creep strain. $\varepsilon_{sh}$ is the maximum strain demand due to shrinkage, while $\varepsilon_e + \varepsilon_i + \varepsilon_{cp}$ is the total material strain capacity. If strain demand exceeds strain capacity, fracture failure occurs in the concrete material.

Table 6 lists the typical range of various strains and cracking potential of normal concrete and ECC. Unlike normal concrete, due to the large tensile strain capacity, ECC has a highly negative cracking potential $P$, allowing shrinkage deformation to be fully accommodated by multiple micro-cracks.

Qian and Li’s study shows a simple linear relation for ECC between tensile strain capacity and deflection capacity under bending test (2007). Given a strain hardening material like ECC, a large deflection capacity also suggests a high tensile strain capacity. From section 3.3, it can be seen that incorporating crumb rubber can improve the deflection of ECC, which may suggest high tensile strain capacity for ECC with crumb rubber. Huang’s recent study also demonstrated that crumb rubber can increase ECC’s tensile strain capacity (2013).

Combining the above conclusions, although compared to ECC without crumb rubber, the drying shrinkage of ECC incorporated with crumb rubber increase from $1050 \times 10^{-6}$ of M1-control mixture to $1660 \times 10^{-6}$ of M3-80CR, it is still one order of magnitude lower than the tensile strain capacity of ECC, suggesting that ECC with crumb rubber can accommodate the shrinkage deformation without localized fracture failure. The following restrained ring test results can further confirm the above statement.

3.5 Ring test for restrained shrinkage

To reveal the influence of crumb rubber on the cracking behavior of ECC under restrained shrinkage condition, M1, M3, M5 were adopted in the ring test. The restrained shrinkage of the ECC mixtures caused compressive strain to be developed in the steel ring. The development of the strain of steel ring with specimen age is illustrated in Fig. 13 for mixtures M1, M3, and M5. As seen in Fig. 13, incorporation of crumb rubber decreases the steel ring strain, indicating a reduced restrained shrinkage of ECC with crumb rubber. This may be caused by stress relaxation effect of rubber particles in cement matrix (Turatsinze and Garros 2008). In addition, there is a slight decrease after peak point for all ECC mixtures with or without crumb rubber, compared with sharp decline in case of normal concrete.

Table 6 Typical range of various strains and cracking potential of normal concrete and ECC (Li and Henrik 2004).

<table>
<thead>
<tr>
<th>Properties</th>
<th>$\varepsilon_{sh}$ (%)</th>
<th>$\varepsilon_e$ (%)</th>
<th>$\varepsilon_i$ (%)</th>
<th>$\varepsilon_{cp}$ (%)</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>0.04-0.1</td>
<td>0.01</td>
<td>0</td>
<td>0.02-0.06</td>
<td>(-0.03) to 0.07</td>
</tr>
<tr>
<td>ECC</td>
<td>0.1-0.15</td>
<td>0.015</td>
<td>2-5</td>
<td>0.07</td>
<td>(-4.99) to (-1.94)</td>
</tr>
</tbody>
</table>
The test results of crack width, total crack length and crack number are summarized in Table 7 and Fig. 14. There are no localized fractures for all ECC ring specimens during testing period, only very tight cracks can be observed on the specimen surface. All specimens show average crack width below 30 μm. In addition, the crack width of ECC incorporating crumb rubber is lower than that of control mixture. Furthermore, lesser total crack length and crack number were observed for ECC mixtures with crumb rubber.

ASTM standard C-1581 specifies the potential for cracking classification according to two parameters: the net time-to-cracking (tcr, in days) and the average stress rate (S, in MPa/day). As no localized fracture appeared on the surface of ECC ring specimens, the net time-to-cracking has no meaning in this test. The calculated results for average stress rate can be seen in Table 8. As shown in Table 8, the potentials for cracking of ECC are classified as moderate-low or low level. Incorporation of crumb rubber leads to a reduction in the quantitative value of potential for cracking, which means lower sensitivity of ECC to cracking due to shrinkage length change.

In summary, although ECC with crumb rubber has higher free drying shrinkage, the results of ring test for restrained shrinkage clearly demonstrate the reduction in cracking tendency of ECC incorporated with crumb rubber, which suggests potential benefits in improving durability of ECC under restrained drying shrinkage condition.

### 3.6 Environment footprint

To evaluate alternative materials’ environment impact, life cycle assessment (LCA) is usually used as an important comparable tool in recent year (Keoleian et al 2005; Qian et al 2013). In this study, a simple comparative LCA analysis of ECCs on CO₂ emission is presented. Figure 15 shows the LCA model of ECC. In this model, it considers all of the raw ingredients’ impact on environment during the whole process of their production, delivery and disposal.

The computations of carbon dioxide (CO₂) emissions of the composites are based on the inventory data of their ingredients in Table 9. The inventory data of all ingredients comes from Chinese life cycle database (CLSD). Waste rubber is usually considered as the waste material, recycling waste rubber will avoid the CO₂ emission during its disposal process, so the CO₂ emission from waste rubber is considered to be negative when calculating. However, crumb rubber is grounded from waste rubber; the grinding process will produce CO₂ emission. Combine the facts that fly ash is a by-product of coal burning power plants and its large demands in the civil construction in China, so the CO₂ emission from fly ash is considered to be zero. The calculation results of the amount of CO₂ emission is displayed in Table 10.

As listed in Table 10, the amount of CO₂ emission shows the decrease trend as the percentage of crumb rubber replacement increase. Compared with ECC without crumb rubber, the CO₂ emission of rubberized ECC with the replacement ratio of 15%, 25% decrease 18% and 30%, respectively. Incorporating crumb rubber into ECC can consume the waste rubber, thus avoid

### Table 7 Restained drying shrinkage behavior of ECC.

<table>
<thead>
<tr>
<th>Mix ID</th>
<th>Crack width (μm)</th>
<th>Crack length (mm)</th>
<th>Crack number</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>27</td>
<td>74</td>
<td>9</td>
</tr>
<tr>
<td>M3</td>
<td>13</td>
<td>53</td>
<td>5</td>
</tr>
<tr>
<td>M5</td>
<td>19</td>
<td>48</td>
<td>5</td>
</tr>
</tbody>
</table>

### Table 8 Potential for cracking classification.

<table>
<thead>
<tr>
<th>Average Stress Rate (S, MPa/day)</th>
<th>M1</th>
<th>M3</th>
<th>M5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13</td>
<td>0.12</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Potential for Cracking</td>
<td>Moderate-Low</td>
<td>Moderate-Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

### Table 9 Carbon intensities of ingredients of various concretes.

<table>
<thead>
<tr>
<th>Ingredients</th>
<th>CO₂ emissions kg-CO₂/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>0.98</td>
</tr>
<tr>
<td>PVA fiber</td>
<td>2.7</td>
</tr>
<tr>
<td>HRWR</td>
<td>1.22</td>
</tr>
<tr>
<td>Waste rubber, grinding</td>
<td>0.62</td>
</tr>
<tr>
<td>Silica sand</td>
<td>0.045</td>
</tr>
<tr>
<td>Waste rubber, disposal</td>
<td>3.18</td>
</tr>
<tr>
<td>Fly ash</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 10 CO₂ emission of ECC (kg/m³).

<table>
<thead>
<tr>
<th>Sand replacement (% Vol.) by Crumb rubber</th>
<th>CO₂ emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>484</td>
</tr>
<tr>
<td>15%</td>
<td>396</td>
</tr>
<tr>
<td>25%</td>
<td>338</td>
</tr>
</tbody>
</table>
environment pollution during its disposal process and provide a disposal method of waste rubber. Meanwhile, it also reduces the volume of silica sand used in ECC, thus reduce the quartz mine exploitation and production of silica sand. Therefore using crumb rubber to replace silica sand help ECC to be more environmental friendly.

4. Conclusions

In this paper, the influence of crumb rubber on ECC mechanical and shrinkage properties were studied. Based on the experimental results and discussions, the following specific conclusions can be drawn:

(1) The density of ECC decreases with the increasing percentage of crumb rubber replacement. The reduction effect of crumb rubber on density is more pronounced when smaller sized crumb rubber is used. The density of ECC with crumb rubber ranges from 1600 kg/m³ to 1710 kg/m³ which can be classified as light weight concrete.

(2) Incorporating crumb rubber increase the flexural deflection capacity of ECC, with the additional benefit of reduced crack width, which is beneficial to its durability. The effect of crumb rubber on ECC flexural deflection capacity is more pronounced when smaller particle size (80CR) is used. However, crumb rubber adversely affects ECC’s strength properties, such as compressive strength and flexural strength, with about 35% reduction of compressive strength.

(3) Drying shrinkage of ECC increases with the amount of crumb rubber in the mixture. Drying shrinkage of ECC for the 80CR case is larger than that of 40CR case under the same crumb rubber content. However, due to the high deformation capacity, ECC with crumb rubber may still be able to accommodate the shrinkage deformation without localized fracture failure. The results of ring test for restrained shrinkage show that incorporation of crumb rubber lowers sensitivity of ECC to cracking due to shrinkage length change.

(4) As the percentage of crumb rubber replacement increase, CO₂ emission have the decrease trend denoting crumb rubber replacement of silica sand help ECC reduce its environmental impact.

Acknowledgments

The authors would like to graciously thank the National Natural Science Foundation of China (No.51008071, 51278097), and the Natural Science Foundation of Jiangsu Province (No.BK2010413), Jiangsu Top Talents in Six Major Fields (2011-JZ-011), Jiangsu Provincial Graduate Student Scientific Research Innovation Plan Projects(No.CXZZ13_0114), China Scholarship Council (CSC) for the financial support for this work. The corresponding author also wants to acknowledge the support of startup grant from Nanyang Technological University, Singapore under Grant No. M4081208.

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